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Structures Technical Memorandum 358

REPORT ON AN OVERSEAS VISIT TO JAPAN, USA AND THE U.K. IN OCTOBER/NOVEMBER 1982

R. JONES

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REPORT ON AN OVERSEAS VISIT TO JAPAN, USA AND THE U.K. IN OCTOBER/NOVEMBER 1982

by

R. JONES

SUMMARY

This is a report on a thirty day visit to Japan, USA and the U.K. from 23rd October to 20th November, 1982. The main purpose of the visit was to attend the 4th International Conference on composite materials which was held in Tokyo from 24th to 28th of October. Following this conference visits were made to the US Army Mechanics and Materials Research Centre in Boston and to the Lehigh Institute of Fracture and Solid Mechanics in Pennsylvania. In the U.K. visits were made to Aston University PAFEC Ltd and the RAE Farborough where discussions were held on damage tolerance, finite element analysis and CAARC.

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1. INTRODUCTION

Here a report is made on a thirty day visit to Japan, the U.S.A. and the U.K. The broad topics with which the visit was concerned were the damage tolerance of advanced composite materials, such as carbon fibre reinforced plastic, and the use of composite materials to repair damage.

The main purpose of the visit was to attend, as an invited chairman, and to present a paper at the 4th International Conference on Composite Materials (ICCM4). This conference was held in Japan from 24th - 28th of October and is the most prestigious forum for the presentation of new ideas and technological advances in the field of composite materials. The first meeting of ICCM was held in Geneva in 1975, subsequent meetings have been held in Toronto in 1977 and in Paris in 1980. The fifth meeting is now scheduled to be in the U.S.A. in the 1984/85 financial year.

Following the ICCM4 meeting visits were made to two US establishments to discuss first hand the demonstrator program on structural repair, being conducted under the auspices of TTCP panel PTP4, as well as recent development in the fracture mechanics of metals and composites. The US establishments visited were the US Army Mechanics and Materials Research Centre and the Institute of Fracture and Solid Mechanics at Lehigh University.

Following the visit to the U.S.A. visits were made to a number of U.K. establishments to discuss (CAARC), the TTCP demonstrator program previously mentioned, the numerical analysis of delaminated fibre composite structures, and developments in the field of fracture mechanics.

Throughout this visit report, the central role that fracture mechanics plays in the understanding of the behaviour of damaged structures, both composite and metallic, will be emphasized. The ICCM4 meeting clearly illustrated how this central role is now becoming widely accepted. This is a major step forward since historically simple "strength of materials" type failure laws have been most commonly used.

2. ICCM4

There were two major areas which emerged from the conference as being the most important and which need much more effort before they will be fully understood.

These were :

(1) The effect of delamination damage on the static and fatigue strength of composites;

(2) the understanding of the temperature-moisture coupling and the curing process of epoxy matrix composites.

This report will concentrate on these two areas.

2.1 Delamination Damage

It was fortunate that most of the research groups actively working on the problem of delamination damage, which may result due to tool drop, poor drilling of holes, manufacturing defects or a variety of other causes, were present at ICCM4 and each group presented their latest work.

The U.S. work focussed on two distinct problems -

(a) Internal delaminations subject to compressive loading.

(b) Edge delaminations.

The edge delamination problem was discussed at length by S.S. Wang from the University of Illinois, whose work is supported by NASA on CR-165439, and by A.S.D. Wang whose work is supported by AFWAL contract number F33615-80-C-5039. Both are looking at essentially the same problem namely a rectangular coupon, which has a delamination running the entire length of the specimen, subjected to either uniform stress or strain in one direction. As has been found at ARL this produces a mixed mode fracture (this point will be discussed in greater detail elsewhere).

In this case the energy release rate quickly reaches a plateau level as the delamination grows into the specimen. This phenomena has been known for some time. However, as has also been found at ARL, both workers show that the delamination may close and that the problem is infact non-linear. Since this problem is essentially two dimensional the energy release rate G provides an excellent tool for establishing the applicability of fracture mechanics principles. In this case the work of A.S.D. Wang [2] is particularly important in as much as it specifically examines the comparison between predicted growth rates, based on an energy release rate model, and those observed experimentally.

Copies of the final NASA and AFWAL contract reports were obtained from S.S. Wang and A.S.D. Wang respectively.

Subsequent discussions look to the possibility that edge notch coupons may be proposed as an ASTM standard for measuring the critical energy release rate G_c for any given laminate.

For the problem of internal delaminations, as opposed to edge delamination, major contributions were made by R. Jones, Australia and by W.A. Dick et al, University of Delaware. In this

case delamination damage results in drastic loss of compressive strength and catastrophic failure may occur at as low as 4000 microstrain. The experimental work undertaken by the Delaware team was of the highest calibre with a large number of laminates being tested. The damage was created by inserting a Kapton or Teflon film between plies and the specimens were examined ultrasonically to determine the extent and nature of the damage propagating from the delamination site. Unfortunately their analysis capabilities did not match their experimental capability and they misunderstood the mechanisms which drive the delamination attributing failure to ply buckling. This aspect of their talk was severely criticized by A.S.D. Wang, S.S. Wang and R. Jones.

Having not seen the difficulties that a number of researchers have in understanding the basic phenomena of delamination growth under compressive loading it came as a surprise to find that ARL was almost alone in its effort to provide a detailed 3-D account of the stresses and the mechanism's driving a delamination undergoing compressive loading. This work, which was presented by R. Jones, was virtually an extension of the work by A.S.D. Wang and S.S. Wang to general three dimensional damage. The phenomena of crack closure and mixed mode growth evident in the 3-D analysis presented by Jones were also evident in the 2-D analysis procedures which have already been discussed.

The mixed mode nature of the deformation field caused a number of investigators to question their own work. Basically what happens around adelamination is that, because of the highly aniostropic nature of the laminate, as it opens it also locally rotates and shears so that in plane loads produce fracture modes I, II and III. It was previously mentioned that the energy release rate may be a useful tool in understanding the delamination problem. A most interesting report on this topic, at least from Australia's point of view, was that of K.N. Street et al. Street examined the role of moisture and humidity on the critical energy release rates. The material chosen for this study was AS1/3501-6, which is the graphite epoxy system used in the F/A-18 wing skin. Because of the coupling involved the measured quantities reported in this paper should not be interpreted as the critical mode I or mode II energy release rates and are in fact combinations of these quantities. The main conclusions which can be drawn from this work is that in the temperature range -50°C to +20°C the critical energy release rate was almost unaffected by either the temperature or the moisture content. However a major change occurred in the temperature range +20 to 100°C.

To date we have concentrated on the reduction in the static compressive strength due to delamination damage. However the work of Stellbrink and Aoki, DFVLR West Germany, clearly illustrated, how these results transform into the fatigue regime. This work concentrated on a graphite epoxy material and seven different ply

Subsequent discussions led to the questioning of the applicability of Fick's law for determining the concentration levels in graphite epoxy laminates. It was pointed out that Springer had mentioned that in some cases involving the transfer of heat and moisture (i.e. the general environmental problem), the two diffusion processes may be coupled and that the simple approach outlined in the plenary lecture may have to be extended. One such extension is described by Crank*, however the tests needed to provide the necessary parameters require extreme accuracy and precision.

The doubts concerning the applicability of the standard moisture and temperature diffusion equations were repeated on several occasions. In this context the work of Lo, Hahn and Chiao, the first two authors being from Washington University the last author being from the Lawrence Livermore National Labs., was particularly interesting. They studies the environmental effects on Kevlar 49/epoxy and S2-glass/epoxy and compared the experimental results with those obtained using

(1) the Classical free phase model (i.e. Fick's law)

(2) the two phase Langmur model for the diffusion of moisture.

From this work it was clear that the two phase diffusion model was a better representation of the diffusion behaviour.

It was also interesting to note that, when considering the swelling behaviour of these two composites, the data points fell onto a straight line with a slope 0.43 regardless of the material system. Thus as a first order approximation the swelling strain e_T^H can be represented by

$$e_T^H = 0.43\ c$$

where c is the moisute concentration. However the reason for the applicability of this approximation requires further investigation.

One major reason for the almost universal use of Frick's law lies in its simplicity. Indeed as explained in the paper by Lien, from Westinghouse Research and Development, standard finite element packages may be used to determine the moisture content if this approximation is used.

2.3 Documents Received

1. Progress in Science and Engineering of Composites, Volumes 1-2, Proc. ICCM4, Tokyo, August 1982.

2. S.S. Wang, Edge delaminations in angle ply composite laminates, Final Report Part V, NASA CR165439, 1981.

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* J. Crank, the Mathematics of Diffusion, Clarendon Press, Oxford 1975, p. 357-359.

3. Pie Chi Chou, A.S.D. Wang and H. Miller, Cummulative damage model for advanced composite materials, AFWAL TR82-4083, 1982.

3. VISIT TO THE U.S.A.

3.1 Visit to AMMRC

At AMMRC detailed discussions were held on several topics. These were arranged by Mr. E. Lenoe the Chief of the Mechanics of Materials Division and also a member of TTCP panel PTP4.

3.1.1 The TTCP Panel PTP4 Demonstrator Program

As part of the TTCP panel PTP4 demonstrator program on repair technology Jones, Australia, has carried out detailed finite element analysis of two repaired panels. This work was discussed at length with Dr. D. Oplinger, who manages the AMMRAC contribution to this program, Dr. R. Barsoum, Dr. D. Sleppetz and Mr. E. Lenoe. In addition a set of lecture notes which had been prepared by Mr. M.J. Davis and Dr. R. Jones, Australia, were given to AMMRC. It had been anticipated that Prof. Fu-pen Chiang, from Stonybrook, would be present. However, Prof. Chiang had recently suffered a stroke and ill health prevented his attendance. This was unfortunate since AMMRC had subcontracted their contribution to this program to Prof. Chiang. Dr. Oplinger indicated that any results obtained would be sent to Australia as soon as possible.

3.1.2 Numerical Analysis of Composites

Dr. Barsoum mentioned that AMMRC is concerned that present finite element methods may not be applicable for the three deimensional analysis of fibre reinforced composites. Indeed he is currently developing a hybrid stress element for use near free edges. We then discussed the technique of reduced integration, as recommended by the Swansea group, and the directionally reduced integration method commonly used at ARL. Dr. Barsoum then remarked that for complex problems an experimental check on these techniques is required. This topic was developed further at the R.A.E. Farnborough.

3.1.3 Moire Methods

AMMRC has spent several years applying moire methods, these are photo-elastic techniques for determining strain fields, to the evaluation of structural performance of composite materials. These methods are particularly accurate and useful in evaluating edge effects, and adhesive joint performance since by examining the edges of a specimen information can be obtained about the interlaminar strains.

This method should prove to be invaluable in examining the interlaminar strains occurring as a result of damage at a metal to graphite joint, such as in the F/A-18. Indeed this is precisely the problem that AMMRC proposes to examine next and Dr. Oplinger asked if ARL would be interested in cooperating on this problem.

At this stage Dr. Oplinger strongly recommended that ARL develop the capability of routinely performing moire analysis. He is convinced that it will be a major tool for the monitoring and the understanding of failures in composite structures.

3.1.4 Laser Damage

A brief description of the effect of laser damage and of the work being done by AMMRC was given by J. Adachi. It was clear that the damage mechanisms, in the case of fibre composite materials, were not yet fully understood. Furthermore testing to date has been for tension and torsional loading whereas it is clear that the reduction in the compressive strength will be greater than the reduction in the tensile strength.

3.1.5 Documents Received

Copies of the following reports were received at AMMRC.

1. D.W. Oplinger, "Application of moire methods to evaluation of structural performance of composite materials", Optical Engng, July 1982, Vol. 21, No. 4, p 626-632.

2. D.W. Oplinger, B.S. Parker and F.P. Chiang, "Edge effect studies in fibre reinforced laminates", Experimental Mechanics, 14, 9, 347-354, 1974.

3. J.M. Slepetz, T.F. Zajaeski, R.F. Novello, "In plane shear test for composite materials", AMMRC TR78-30, July 1978.

3.2 Visit to Lehigh University, Institute of Fracture

The main contact at the Institute of Fracture and Solid Mechanics at Lehigh University was Professor G.C. Sih who is the director of the Institute. Professor Sih is a leading US authority on fracture mechanics and has published numerous books on the subject. Indeed one reason for visiting Lehigh was to discuss developments in the publishing of the proceedings of the International Conference on Fracture Mechanics and Technology which was held in Melbourne in August 1982 and for which the editors are Prof. Sih, Dr. R. Jones and Dr. N.E. Ryan, the last two being from ARL. The proceedings is being published by Martinus Nijhoff and has reached the stage where it is now ready for publication.

Professor Sih has fifteen Ph.D. students working for him and they work on problems varying from bio-mechanics through to ductile fracture and the fracture of concrete.

3.2.1 Fracture Mechanics

The main problem discussed in this field was that of the failure of composites which contain delamination damage. Since the mode of growth is non self similar (i.e. ellipses do not grow into confocal ellipses) and since the failure mode is mixed (i.e. it will not be pure mode 1, etc) Professor Sih did not believe that the J integral, which is widely used for self similar crack growth in metals, is at all applicable. Nor did he believe that the energy release rate would be useful except in the simple two dimensional problems under study by A.S.D. Wang and S.S. Wang (see section 2.1). Professor Sih preferred the strain energy density concept and was pleased to see that this was one of the two approaches used by Jones et al in the paper presented at ICCM4.

On the subject of subcritical delamination growth Professor Sih recommended that the growth of the delamination be calculated assuming that at each point along the front the same amount of strain energy is released. Indeed the recent book by Sih and Theorcaris contains a significant amount of experimental verification for this approach. A copy of this book was provided by Professor Sih.

It was mentioned that this approach requires values for the critical strain energy density levels in the epoxy. Professor Sih indicated that these critical values can be determined from simple tensile tests on unidirection specimens. A copy of the report outlining this technique was also provided.

3.2.2 Environmental Effects

As was mentioned in section 2.2 the standard diffusion equations for the diffusion of temperature and moisture into a fibre composite laminate are now being seriously questioned. Professor Sih said he thought that the standard equations were far too simplistic and that he preferred the coupled system of equations given by Crank for the simultaneous diffusion of heat and moisture. He said that work at Lehigh had conclusively shown that, for Narmco Thornel T300/5208, the interaction of heat and moisture can significantly alter the stress distribution. A copy of this and related work was provided. In this context the work of Sih, Shih and Chou is particularly important in as much as it compares the various theories paying particular attention to the stresses in the laminate.

3.2.3 Laser Damage

Professor Sih is currently working for the US Naval Research Laboratory on the prediction of failure sites ahead of a moving energy source (i.e. laser damage) and had recently produced a report co-authored by Dr. C.I. Chang, from the N.R.L. in Washington, on this topic. This report presents closed form analytical solutions for the temperature and the resultant stress distributions surrounding the energy source. Professor Sih said that whilst this report deals with metallic structures work is also in progress on the analysis of damage to composites.

Professor Sih also indicated that he was currently organising a workshop in Australia on "Laser Technology Applied to Evaluation of Material and Structural Integrity". It is proposed that this workshop be run jointly by Melbourne University and Lehigh University with six eminent scientisits being brougnt out from the USA, their expenses being met by the National Science Foundation. ARL was invited to participated in the workshop

3.2.4 Documents Received

1. G.C. Sih and C.I. Chang, Prediction of failure sites ahead of moving energy source, Proc. Int. Conf. on Fracture Mech. and Technology, Melbourne, Australia 1982.

2. G.C. Sih, P.D. Hilton, R. Badaliance and G. Villarneal, Exploratory development of fracture mechanics of composite systems, AFML-TR-70-112 part III, January 1973.

3. G.C. Sih, M.T. Shih and S.C. Chou, Transient hygrothermal stresses in composites: coupling of moisture and heat with temperature varying diffusivity, Int. J. Engng Sci., 18, pp 19-42, 1980.

4. G.C. Sih and M.T. Shih, Hygrothermal stress in a plate subjected to antisymmetric time dependent moisture and temperature boundary conditions, Journal of Thermal Stresses, 3, 321-340, 1980.

5. R.J. Hartranft and G.C. Sih, Stresses induced in an infinite medium by the coupled diffusion of heat and moisture from a spherical hole, Engng Frac. Mech. 14, pp 261-287, 1981

6. Mixed mode crack propagation, edited by G.C. Sih and P.S. Theocaris, Sijthoff and Noordhoff publishers, 1981.

4. VISIT TO U.K.

4.1 Aston University

At Aston University discussions were held with Professor J.T. Barnby, head of the Metallurgy department, concerning the short bar fracture toughness test. This test procedure was developed by Professor Barnby and enables true fracture toughness measurements to be made for specimens whose thicknesses are well below those required by the ASTM E399 standard method. This procedure involves the application of an opening load to the mouth of the short-rod or short-bar specimen which contains a chevron shaped slot. Load versus deflection across the slot at the specimen mouth is recorded. As the load is increased a crack initiates at the point of the chevron slot and slowly advances tending to split the specimen. The load goes through a smooth maximum when the width of the crack front is about one third of the specimen diameter, or breadth (short-bar). Thereafter the load decreases with further crack growth. The fracture toughness is calculated from the maximum load in the test and residual stress and plasticity parameters are evaluated from unloading-reloading cycles.

Professor Barnby explained that this method was currently being evaluated by ASTM prior to recommendation as a standard. However the S.A.E. have adopted it as an aerospace recommended standard (viz: ARP-1704). It clearly represents a major advanced in fracture toughness testing. A machine which is capable of routinely testing any such short-bar or short-rod specimen is now available through Terra Tak. Inc. Salt Lake City, Utah under the name Fractometer II.

Professor Barnby is currently working on ductile fracture, under contract from the U.K. Atomic Energy commission, in an attempt to understand the basic phenomena. Because of ARL's excellent reputation in numerical fracture mechanics, he inquired if we would like to co-operate on the work with the numerical investigation being done at ARL and the experimental work at Aston University. A formal invitation is to be sent to ARL.

4.2 PAFEC Ltd., Nottingham

PAFEC Ltd supply the general purpose stress analysis program PAFEC75 currently in use at ARL. Indeed whilst at PAFEC level four of this program and level two of the interactive graphics program PIGS was released by PAFEC. These levels are a major improvement on the current levels in use at ARL and will be installed at ARL early in February 1983. One of the major improvements in the plasticity facility which now allows for unloading. This facility was implemented by Dr. Alan Stafford, who spent five weeks at ARL in 1981, and was one of the new facilities that ARL had requested.

The greatest improvement was in the interactive graphics program PIGS. This now allows full interactive mesh generation and for data entry from a graphics tablet. In the past mesh generation was confined to the main program PAFEC75 and as such was not interactive. This will greatly simplify the task of analysing cracked structures with complex crack shapes.

4.2.1 Fracture Mechanics

Discussions were held with Mr. Dick Stevens on the 3-D J integral currently being developed for ARL at a cost of $1000. This is to be applicable to metallic and to layered anisotropic material. It is clear that PAFEC Ltd. significantly underquoted for this task, and the J integral will not now be ready until January 1983. Nevertheless once developed this facility will significantly enhance PAFEC75 capabilities, particularly in the analysis of damaged composites, and should as a result boost their sales.

In the past year ARL has made significant use of PAFEC75 in the field of elastic plastic fracture and copies of the ARL report were given to Dr. R.D. Henshell. Dr. Henshell, the managing director, mentioned that this was a very important and growing area in the U.K. but one in which PAFEC has as yet done little work. He was particularly pleased to see how useful PAFEC was in this field. It was then mentioned that PAFEC only gives equivalent plastic strains and that ARL requires the full stresses and strains. As a result of this Dr. R. Jones, ARL, and Dr. A. Stafford modified PAFEC to meet ARL requirements. These modifications have subsequently been implemented at ARL.

4.2.2 Aspect Ratio Limitations

Discussions were held with Mr. Neil Rigby on the use of reduced integration and double precision, which are both used at ARL, for long and narrow elements. These elements occur when analysing damage in graphite epoxy laminates. Unfortunately this is not a problem which PAFEC have investigated. However Mr. Rigby did mention that Wimpy Offshore Engineering Services, in Hayes Middlesex, were examining the use of elements with large aspect ratios.

4.2.3 Current and Future Developments

In August 1982 ARL tendered for a three dimensional plasticity module. This tender was discussed at length with Dr. A. Stafford. It was pointed out that to be effective ARL needs this facility to work in conjunction with prescribed initial strains. (This problem is directly connected with the cold work hardening procedure used to extend the life of fatigue critical components). As a result of this discussion it was clear that PAFEC could easily meet ARL's requirements.

Discussions were also held with Dr. R.D. Henshell and Mr. N. Rigby concerning the modelling of a moving energy source (i.e. a laser beam). Here the problem is that the energy source degrades the material so that the stiffness matrices change with time. After extensive discussions a simple procedure for analysing this problem was developed. Dr. Henshell indicated that PAFEC would be willing to build this procedure into the PAFEC75 suite of programs for £2000.

4.3 Visit to the RAE Farnborough

The main contact at the RAE was Dr. A.J. Sobey from the Materials and Structures Department. Dr. Sobey has recently been nominated for the position of CAARC Chief Coordinator for Structures. Detailed discussions were held on a variety of topics. These discussions are described below.

4.3.1 Repair Technology

The demonstrator program on repair technology being undertaken through TTCP panel PTP4 was discussed at length.

The RAE was particularly interested to know that work at ARL had confirmed that the simple formulae, developed at Northrop, to accout for the reduction in patch efficiency due to bending effects was very accurate and agreed well with detailed analysis.

At this stage it should be mentioned that the U.K. is not actively participating in the demonstrator program. Instead they are persuing an in-house program which involves the patching of centre notch aluminium alloy panels. The panels are a 7475 Aluminium alloy and are patched on one side only. To date their program has shown that after patching the stress intensity factor, for long cracks, is independent of crack length. However, Dr. N. Wilson remarked that after patching short cracks appear to have a larger stress intensity factor than long cracks. This was particularly interesting since the same phenomena has been observed at ARL in both laboratory tests as well as in computer studies. Indeed this phenomena is an integral part of the TTCP demonstrator program.

The RAE have identified the adhesive layer as the most critical component in bonded repairs and are attempting to optimize bond durability. To this end a number of adhesives are being investigated over a significant temperature range.

Whilst testing is currently underway in a salt solution it is planned to fatigue specimens under the Falstaft loading program and in a controlled environment with variable temperature and moisture. It is also planned to study the repairability of Titanium sheets.

At this stage the RAF is very interested in the progress being shown at the RAE as is British Aerospace. The RAF are particularly interested in developments concerning the repair of primary and secondary structures. Mr. Sobey mentioned that Westlands are interested in the application of crack patching technology to helicopters.

4.3.2 RAE Box Beam Program

A detailed list of questions concerning the RAE box beam program, which is very similar to the proposed program being developed at ARL, was tabled and discussed at length. These questions together with the corresponding anseres are given in the appendix.

Until recently the box beam test had been run by Mr. R.F. Mousley. However, with the amalgamation of Structures and Materials Departments into the new Materials and Structures Department Dr. John Sturgeon has taken over the task. The test is currently in suspension due to an increase in the acoustic emission and the box beam is being extensively examined for damage. The areas surrounding the impact damage and the inbuilt delaminations have been monitored continually throughout the test. Yet there has been no sign of damage growth at these locations. This indicates that the acoustic emission may be coming from the metal substructure. The maximum strain reached prior to suspending the test was well below the 4000μ level which is thought to be necessary for the delamination damage to grow.

4.3.3 Damage Tolerance of Composites

The RAE has recognised that one of the major limitations in the use of graphite epoxy laminates is the degradation in compressive strength due to interply delamination. Furthermore in order to assess the need to repair delamination damage a method of assessing criticality must be devised. Recent tests conducted by Richard Poole on a $(0/\pm45/90)_{4S}$ graphite epoxy laminate, which has been subjected to impact damage, revealed that the majority of growth occured between the ±45 and -45 degree plies nearest the surface (i.e. between the 2nd and 3rd plies). This is particularly interesting since this location was also found to be critical in the numerical study of Jones et al which was presented at ICCM4.

In the coupon tests conducted at the RAE the edges of the specimen are prevented from out of plane movement. Various methods for doing this were discussed. These varied from simple knife edge supports to using a thick walled tube with slits cut in the interior to accommodate the specimen.

Because of ARL interst in delamination failure it was suggested that ARL might like to participate in a joint exercise with the RAE on this topic. It was proposed that the RAE would construct several coupons with inbuilt delamination damage between the 2nd and

3rd plies. The ply lay ups to be considered are

(a) $(0/\pm45/90)_{3S}$

(b) $(0/\pm45/90)_{4S}$

In the case of (a) the specimen dimensions will be 4" x 3" and will contain a centrally located and inbuilt delamination 3/4" x 1". For specimens constructed from lay up (b) the dimensions will be 4" x 14" and will contain a 1 x ½" delamination. The specimens will be tested under compression at the RAE with the surface strains and the out of plane bending being recorded.

The surface strains, out of plane deformations and internal stresses will be computed at ARL for each specimen. The strain energy density and the J integral concepts will be used to predict the failure loads.

One aspect of this exercise is to see if present computational techniques are capable of predicting surface strains in the vicinity of a delamination. This is by no means a trivial problem since the small ply thicknesses (e.g. 0.005") result in elements with large aspect ratios and cause the problem to become ill conditioned. If these quantities are not capable of being accurately predicted then additional research is necessary in order to improve our computational capabilities.

This work is to be done under CAARC and its successful completion will simplify the prediction of flaw criticality in any given graphite epoxy laminate (e.g. the wing skin of the F/A-18L).

As part of the delamination damage program the RAE is also investigating the effect of impact damage on composite I beams and on a "little" I beam which is 7½" wide and 4" deep where the effect of damage in the web is being investigated.

4.3.4 CAARC Collaborative Work

Mr. A.J. Sobey, previously a U.K. specialist in Fracture Mechanics, has recently been nominated as the CAARC Field of Structures Chief Coordinator. Mr. Sobey will replace Dr. F.H. Hooke from ARL. To ensure that effective collaboration occurs it is now proposed to hold regular CAARC coordinators meetings and to ensure that each country's representative is present. Consequently the cooperative program, mentioned above, on delamination damage is most timely.

Mr. Sobey mentioned that in helicopters and aircraft the highly directional properties of fibre reinforced plastics are being increasingly used for aeroelastic tailoring. In these cases

correct values for the interlaminar moduli (i.e. G_{13}, G_{23}, E_{33}, γ_{13}, γ_{23}) are vital. Unfortunately no standard test procedures for these moduli have been agreed on. We agreed that the standardization of these test procedures would be an excellent cooperative program and Mr. Sobey decided to propose it at the next CAARC coordinators meeting.

4.3.5 Documents Received

1. D. Purslow, Some fundamental aspects of composites fractography. Composites, p 241-247, October 1981.

2. A.J. Sobey and E.H. Mansfield, The fibre composite helicopter blade, R.A.E. Technical Report 78139.

3. D.J. Allman, Improved finite element models for large displacement analysis and post buckling analysis of thin plates, Int. J. Solids and Structures 18, 9, 737-762 (1982).

4. J.J. Brown, R.A. Christ, K.L. Kilroy and G.R. Parker, A unified approach to helicopter Nastran modelling, Proceedings American Helicopter Society Northeast Regional Specialist Meeting on Helicopter Vibration, Hartford, Connecticut, Nov. 1981.

5. D.H. Woolstencroft, A.R. Curtis and R.I. Haresceugh, A comparison of test techniques used for the evaluation of the unidirectional compressive strength of carbon-reinforced plastic, Composites, p 275-280, October 1981.

APPENDIX A

TESTING OF CARBON FIBRE BOX BEAM SPECIMEN

ARL wish to benefit from the experimence of others who have carried out work on the British Aerospace Test Box. The provision of any information regarded as being of assistance to ARL in undertaking this project, would be greatly appreciated. Below please find listed questions on aspects of the task which we consider important.

(A) Design of Test Rig

ARL would be pleased to receive information in the form of engineering drawings, schematics and photographs illustrating what is considered to be a test rig of correct design; we have a partial set at the moment.

In particular we would like to know of any special design features, for example the application of load to the specimen (i.e. specimen gripping). Does specimen gripping require special attention?

(B) Hydraulic Loading System

(a) Circuit diagrams of the system and details of any special features would be useful.

(b) What type of hydraulic actuators are used?

(c) Are the hydraulic actuators locked up in case of specimen failure to prevent damage of fracture surfaces?

(C) Dummy Test Specimen

At ARL it is common practice, especially on smaller test rigs, to make use of a dummy test specimen for rig cycling trials prior to fitment of the actual test specimen, i.e. to ensure that the control system is functioning correctly.

Are dummy specimens used, if so what is the suggested design of such an item?

(D) Inspection Techniques

ARL would be pleased to receive information regarding the recommended non-destructive inspection techniques used on the specimen, together with advice on those areas of the specimens requiring most frequent inspection.

(E) Strain Gauging and Calibration

(a) What are the recommended strain gauge locations and what type of gauges and adhesives are utilized?

(b) Are there any special calibration procedures?

(c) What are the recommended procedures for static calibration?

(F) Design of Environmental Chamber

(a) Are there any special design features, e.g. baffles?

(b) How is uniform temperature distribution achieved?

(c) Is removal of excess moisture a problem?

(d) In regard to chamber instrumentation, what is the best location for temperature and humidity, probes and what other chamber instrumentation is required?

(G) Conditioned Air Supply

(a) Are there any special considerations when using this equipment?

(b) Are there any problems associated with the use of this type of equipment?

(c) Mass Flow: What are the recommended limits of mass flow (upper and lower) through the chamber?

APPENDIX B

RAE ANSWERS TO QUESTIONS ON THE BOX BEAM TEST

1. These brief notes are in response to a request from ARL, but only give answers from a user point of view. They cover the experience gained testing a mixed composite/metal box beam (E1) in fatigue up to 1 August 1982.

2. The test rig design was described in general terms in a letter to Brian Hoskins, dated 20 March 1980.

3. Generally the rig and control equipment designed by A.J. Beard was entirely satisfactory as used in constant amplitude fatigue up to non-damaging levels. Prior to this use it had satisfactorily tested a massive dummy beam of rolled steel joints etc up to destruction. Delays in test commencement were entirely due to specimen procurement which gave various problems, and resulted in a box conditioned naturally to ambient moisture.

4. Specimen gripping was by standard engineering stock or joists with 1/8 in hard rubber interlay. No problems were encountered.

5. Lubrication of load bearing pins taking fatigue forces from the jacks to the grips was necessary. Some attention should be given to the engineering design of such links.

6. Whilst Warton have used a displacement control on one jack to stabilise static tests of similar boxes, RAE did not for fatigue testing. Rotation of the beam in a rigid mode about the central reaction beam would cause limit trips to operate, however only small and occasional manual adjustments of zeroes were necessary to prevent this.

7. The test dummy for rig proving and setting-up was designed for high stiffness and ease of construction.

8. NDI can be divided into checks on the continuing integrity of the entire specimen; and damage growth measurements of the inserted damage areas.

Strain gauging checking on the distribution of loads in the skin bays and booms gave a gross check on box integrity. Otherwise conventional inspection was applicable to the metal completion structure.

a. AE measurements which it had been expected might locate sources of activity in the box and give an indication of where to attend to other inspection techniques gave equivocal results. This problem is still under investigation. Certainly increased activity was found with increasing strain amplitude and also increased activity with numbers of cycles. However location of sources was not possible with

the system as employed, although generalisation about which area was more active could be made. This situation may in part be a reflection on the complexity of the structure.

b. Field strain measurements using an optical moire proved difficult because of the large out-of-plane component of movement which gave false dilations due to perspective. Independent displacement measurements allowed corrections to be made. Replica techniques might be more appropriate if otherwise satisfactory. Shadow moire was used to check the gross out-of-plane movements but since has been used for more detailed investigation of the local buckling at damage in compression coupons, and might be applicable to structures.

c. Most successful use of ultrasonic techniques was made with a transducer applied to the damaged areas and mounted on a cross-frame to give coordinates. The couplant used was glycerol. The job needs dedication on the part of the operator but is capable of giving delamination contours to within ±1 mm and one ply resolution. The results showed that no growth was occurring at the levels used. Only the artificial delaminations at bolt holes gave no signal, possibly due to the closing pressure.

9. Date collection from strain gauges requires a good logger with programming facilities to flag changes in the groww strain distribution immediately.

10. We have not used environmental systems on this box.

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16. Abstract

This is a report on a thirty day visit to Japan, USA and the UK from 23rd October to 20th November, 1982. The main purpose of the visit was to attend the 4th International Conference on Composite Materials which was held in Tokyo from 24th to 28th of October. Following this conference visits were made to the US Army Mechanics and Materials Research Centre in Boston and to the Lehigh Institute of Fracture and Solid Mechanics in Pennsylvania. In the UK visits were made to Aston University PAFEC Ltd and the RAE Farborough where discussions were held on damage tolerance, finite element analysis and CAARC.

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